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Continuous active-source seismic monitoring of CO_2 injection in a brine aquifer

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ABSTRACT

Continuous crosswell seismic monitoring of a small-scale CO_2 injection was accomplished with the development of a novel tubing-deployed piezoelectric borehole source. This piezotube source was deployed on the CO_2 injection tubing, near the top of the saline aquifer reservoir at 1657-m depth, and allowed acquisition of crosswell recordings at 15-minute intervals during the multiday injection. The change in traveltime recorded at various depths in a nearby observation well allowed hour-by-hour monitoring of the growing CO_2 plume via the induced seismic velocity change. Traveltime changes of 0.2 to 1.0 ms (up to 8%) were observed, with no change seen at control sensors placed above the reservoir. The traveltime measurements indicate that the CO_2 plume reached the top of the reservoir sand before reaching the observation well, where regular fluid sampling was occuring during the injection, thus providing information about the in situ buoyancy of CO_2.

INTRODUCTION

Subsurface storage of CO_2 for greenhouse gas mitigation is expected to require monitoring to verify that CO_2 remains effectively trapped underground (Benson et al., 2005). Time-lapse seismic imaging has been shown to be an effective technique for subsurface CO_2 monitoring in both enhanced oil recovery (Lazaratos and Marion, 1997; Wang et al., 1998; Gritto et al., 2004; Majer et al., 2006) and sequestration (Skov et al., 2002; Arts et al., 2004).

The monitoring and quantitative estimation of CO_2 injected into saline aquifers is potentially simplified by the single liquid phase in the reservoir, compared with the multiple phases present in oil reservoirs (often with oil, methane, and saline, e.g., Hoversten et al., 2003). Recent work (Xue et al., 2005; Daley et al., 2007) has shown that borehole seismic techniques (VSP and/or crosswell) can image the in situ change in seismic velocity caused by the displacement of brine by supercritical CO_2. Current borehole seismic techniques typically require dedicated boreholes for wireline deployment and are limited to discrete time snapshots which are repeated to generate time-lapse imagery.

In this paper, we present the methodology of a novel crosswell seismic monitoring approach applied to a CO_2 injection, which allows continuous monitoring through use of a borehole source deployed in the injection well. We first present the background and the experiment design, along with motivating factors, followed by a description of a unique borehole source developed for this experiment, including a detailed review of tubing deployment of both the source and the sensor array. Then we present initial results of the CO_2-injection monitoring with interpretation, followed by conclusions.

BACKGROUND

In 2004, a 1600-ton CO_2 injection into a brine aquifer at 1530-m depth with associated monitoring activities constituted the Frio-I test (Hovorka et al., 2006). The Frio test site in southeast Texas near the Gulf of Mexico has two wells, an injection well and a dedicated monitoring well that is offset 30-m updip. Time-lapse crosswell tomographic imaging of the Frio-I CO_2 plume demonstrated that large changes in seismic velocity (a 500 m/s decrease within the plume) were caused by the injection of supercritical CO_2 into the brine reservoir (Hovorka et al., 2006; Ajo-Franklin et al., 2007; Daley et al., 2007;). Following the Frio-I test, planning began for a second small-scale injection of about 300 tons of CO_2 in the 17-m-thick Blue sand reservoir at 1650-m depth at the Frio site. The Blue sand has similar porosity (about 25%) and permeability (>2 darcy) as the Frio-I sand. A description of the Frio site and Frio-I results is given in Hovorka et al. (2006).

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FRIO-II SEISMIC EXPERIMENT DESIGN: CONTINUOUS ACTIVE-SOURCE SEISMIC MONITORING (CASSM)

The Frio-II experiment had a goal of monitoring CO_2 plume migration under conditions strongly affected by the buoyancy of CO_2 in the brine aquifer. Monitoring buoyancy required geophysical measurements because fluid sampling in the observation well could not be relied on to detect the depth of initial CO_2 breakthrough within the reservoir interval. The large seismic velocity change measured in the Frio-I test suggested that continuous monitoring of crosswell traveltime during injection could detect CO_2 saturation changes along a given raypath. Therefore, we designed a crosswell continuous active-source seismic monitoring (CASSM) experiment in which data would be acquired continuously during injection along a set of fixed raypaths (Figure 1).

Conceptually, if the CO_2 saturation and/or plume thickness increased along a given raypath, the traveltime would decrease, thereby allowing detection with some spatial resolution, especially in the vertical direction. We chose the source location near the top of the reservoir sand at 1657 m to maximize the resolution in the upper sand and to minimize the chance of CO_2 accumulation in the near-source volume. Seismic ray trace modeling was used to estimate the region of the reservoir expected to be monitored by a given source-sensor raypath. The model had five layers in the reservoir zone with velocities derived from a sonic log of the injection well. We assumed the volume sampled along each raypath was controlled by wavelength (about 2.5 m at 1 kHz).

Obtaining continuous crosswell seismic data required deploying the seismic source and sensors via production tubing concurrently with a geochemical fluid sampling system. Fluid sampling in each well was to be accomplished with a U-tube design (Freifeld et al., 2005) for sampling below the packer used for isolating casing perforations. The seismic source would be above the injection well packer and in the well fluid, rather than below the packer where it would be in supercritical CO_2. The seismic sensors (hydrophones) also needed to be deployed on production tubing, both above and below a packer in the observation well. The relative locations of source, sensors, packers, and perforations are shown in Figure 1.

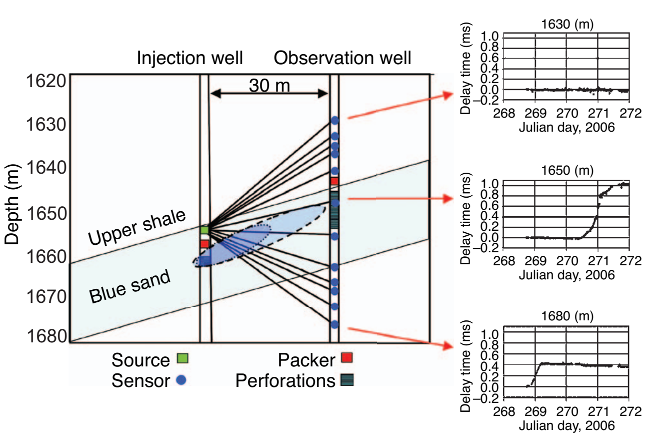

Figure 1. Schematic of Frio-II seismic monitoring experiment with conceptual CO_2 plume after one day (inner short dash) and after two days (outer long dash), with measured delay times at three sensor depths over three and a half days of CO_2 injection (right).

Piezotube source design and injection well deployment

The well casing size of 0.124-m (4.9-in) inner diameter provided a challenge for equipment design. The seismic source needed to be deployed on the outside of standard 0.060-m (2.375-in) production tubing, leaving an annular space of about 0.032-m width. To address this limitation, a novel piezotube source was designed (Daley et al., 2006). The piezotube source was designed as a hollow tube of piezoelectric material with an offset center (to increase annular space on one azimuth) which could slide onto the production tubing and be clamped in place at any selected location. The source could then be deployed at depth for the duration of the injection.

Previous success using CASSM to investigate velocity-stress sensitivity (Silver et al., 2007) encouraged us to select a piezoelectric source because of repeatability and durability (millions of excitations without failure). The relatively low amplitude of piezoelectric sources compared with that of mechanical sources can be partly overcome by stacking because the source would remain in one location indefinitely.

Figure 2a shows a photograph of the source exterior and interior along with a schematic representation. The source has an outer diameter of 0.12 m (4.6 in) and an inner diameter of 0.08 m (3.25 in), allowing room for the 10-mm-thick piezoelectric ceramic rings. There are 18 rings stacked vertically between the outer 1.8-mm-thick stainless steel shell and an inner fiberglass mandrel (7.6 mm thick). The mandrel provides support for the piezoelectric rings and electrical isolation between the source and the production tubing. The mandrel has an offset center, i.e., the axis of the source is not coincident with the axis of the production tubing, allowing room for instrumentation to pass through the source.

In our experiment, we have two 9.25-mm (0.375-in) tubes (one for fluid sampling, one for packer inflation) and one signal cable for a pressure/temperature tool mounted below the source and the packer (within the perforated injection interval). These three lines pass between the production tubing and source mandrel. Above the source, these three lines along with a coaxial cable for source power are clamped to the production tubing during deployment, with protection at each tubing coupling, every 9.1 m (30 ft). A piston-type pres-

a) b)

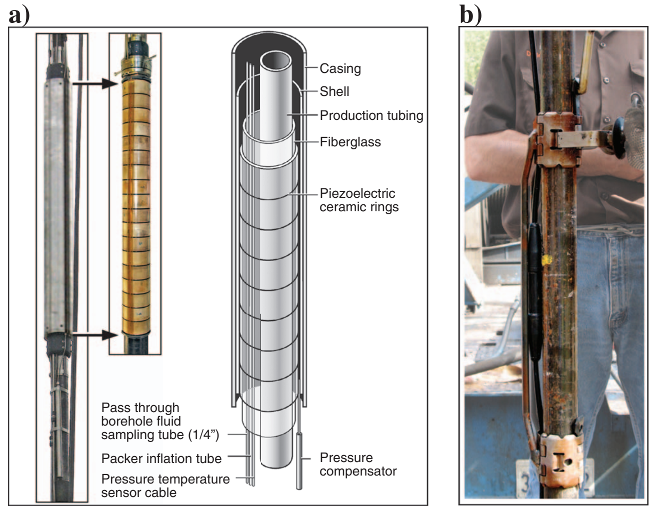

Figure 2. (a) Piezotube source, as deployed (left), interior without shell (center) and in schematic (right). (b) Hydrophone as deployed on tubing with protector/clamp.

sure compensator equalizes borehole fluid pressure with the internal insulating fluid (a commercial product named DIALA-AX).

Seismic sensor design and deployment

The seismic sensors were placed in the observation well to avoid the substantial acoustic noise generated by CO_2 flow expected within the injection well. Hydrophone sensors, rather than geophones, were used to remove the need for clamping to the outer casing and for better high-frequency response ($\sim$ 1 kHz) appropriate for the expected spectrum of the piezoelectric source. The 24 hydrophones (Benthos model AQ-503-1-2 which include an active amplifier) were small diameter (31.75 mm) and were molded into a multiconductor cable that had insulation with an outer layer of polyether (Estane #58887 by Noveon Inc.) to minimize CO_2 permeability. The cable was fabricated by VCable, LLC.

The equipment installed in the observation well consisted of the 24 hydrophone seismic sensors on their cable, a U-tube for fluid sampling (Freifeld et al., 2005), a pneumatic packer to isolate the reservoir sand, and a pressure/temperature sensor below the packer in the perforated interval. The equipment was installed on 0.07-m (2.625-in) production tubing. The installation used commercial, custom-designed cable and sensor protector/clamps (Cannon Services, Ltd.) designed to prevent damage during installation and support the cables and sampling tubes on the production tubing (Figure 2b). Protector/clamps were placed on each tubing coupling and each sensor (except for the first sensor below the packer). Where the sensor cable passes through the packer, a jumper cable with commercial subsea electrical connections (by SEA CON Brantner & Associates, Inc.) on each end was installed. This jumper cable was necessary to allow connection of the cable segment below the packer to the upper cable during deployment at the wellhead.

The sensor locations included depths above and below the packer, which was deployed at the top of the reservoir sand and above the perforations as shown in Figure 1. In the initial installation, seven sensors were above the packer and 17 were below with 2-m spacing. Despite the sensor protectors, several sensors failed during installation or had degraded signal quality, leaving 13 monitoring sensors with variable spacing (five above the packer and eight below). The cause of failure currently is unknown, because the equipment is still deployed in the well.

The sensors above the packer are also above the reservoir sand in a shale unit. Because the shale unit is relatively impermeable and CO_2 is not expected to enter the shale unit, we expected that these sensors would not have any change in traveltime until the CO_2 moved up to the source itself. Therefore, the sensors above the packer serve as a control of monitoring repeatability (precision).

SEISMIC MONITORING OF THE CO_2 INJECTION

The instrumentation deployment was completed on September 20, 2006. Initial testing demonstrated that good quality seismic data could be acquired. Continuous acquisition began on September 25, 2006 (Julian day 268). The source pulse was a 1.0-ms square wave with 3-kV peak-to-peak voltage applied. The source was pulsed four times per second.

Although signal-to-noise ratios (S/N) were poor (one or less) for individual source pulses, extensive stacking was possible and planned. Figure 3a shows a preinjection gather with a stack of 1200 pulses per trace (about 5 minutes of stacking). Operational issues required varying the source repetition rate, but generally, data were stacked into 15-minute intervals with at least hundreds of pulses in that period. Previous work (Silver et al., 2007) shows that with similar acquisition systems the S/N increases as the square root of the number stacks for up to 10^4 stacks (implying nonrandom system noise is not a factor).

The data repeatability (a key parameter for monitoring and essentially a function of S/N) was very good for the 13 functioning sensors, with S/N greater than 20 for 1200 stacks and repeatability measured as an average preinjection time change of 11 μs. Fortunately, the 13 good sensors spanned the study interval, allowing monitoring of the volume as designed but with reduced spatial sampling. The preinjection monitoring (Figure 3a) established baseline traveltimes.

However, during this preinjection operation, we observed that the seismic source was causing interference with data from a downhole pressure sensor in the injection well (presumably caused by voltage induced from the high-voltage seismic source into the low-voltage signal cable of the pressure transducer). Because of this interference, the seismic source was not run during the first two hours of injection to allow detailed pressure measurements. CO_2 injection began at approximately 7:30 pm, Central Daylight Time, on September 25, 2006 (Julian day 268.8 in Figures 1 and 4), the seismic monitoring system was operated intermittently (about 5–8 minutes of stacking at four pulses per second in every 15-minute interval) to produce data on approximately 15-minute intervals.

Figure 3b shows seismograms for the first three days of monitoring with a clear change in traveltime. Figure 4 shows a plot of delay time (traveltime minus initial preinjection traveltime) for five sensors—four below the packer and one above. In Figure 1, data from three sensors are placed alongside the schematic raypaths to show the spatial relationship of the measured time changes. In Figure 4, the deeper sensors (1680 and 1666 m) show a sharp increase in delay time beginning only 3–4 hours after injection with stabilization at about 0.4-ms delay after about 15 hours. The 1658-m sensor shows a more gradual increase in delay time beginning at about 8 hours after injection and stabilizing at about 0.25-ms delay after about 36 hours. The 1650-m sensor, which has a raypath along the top of

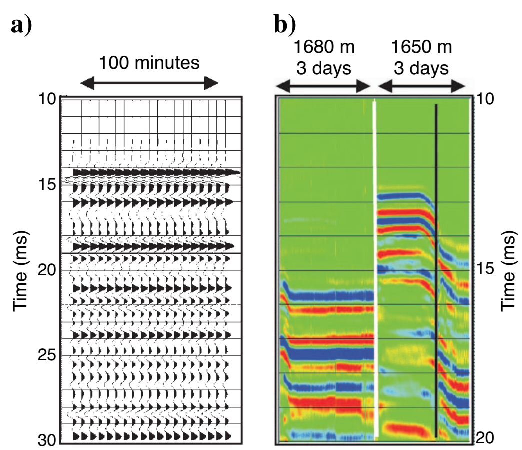

Figure 3. (a) Preinjection monitoring data for 1670-m sensor depth showing excellent repeatability for stacking of about five minutes per trace. (b) Monitoring data of 15 minutes stacking per trace for 1680-m (left) and 1650-m (right) depths showing changes in traveltime caused by CO_2 injection. Sensor at 1650 m (top of reservoir) shows a clear change in time of first arrival before breakthrough was observed via fluid sampling in the monitoring well (solid black line).

the reservoir, begins to delay after about 36 hours and stabilizes at about 1-ms delay after about 70 hours. The observed delay times of 0.2 to 1.1 ms represent 1% to 8% changes in traveltime.

Above the packer (1630 m and others not shown), there is no significant, systematic change in traveltime. The lack of change above the packer demonstrates that the below-packer changes are in the subsurface and that the near-source volume has not been affected by the CO_2 injection. Therefore, the observed delay times can be interpreted in terms of CO_2 plume migration and/or saturation changes.

Processing and analysis of the entire CASSM data set (over 10 days at 15-minute intervals) is in progress at the time of this writing. However, on-site data processing and analysis did provide day-by-day initial results including the detection of CO_2 at the top of the sand before breakthrough was observed in the monitoring well via fluid sampling (at 20:42 hours on September 27, 2006, Julian day 270.9). An example of on-site data is shown in Figure 3b, which shows seismograms recorded over three days with the sensor at 1650 m (raypath along the top of the Blue sand). A large decrease in traveltime appears well before the fluid-sampling breakthrough.

INTERPRETATION

The injection of CO_2 causes a decrease in seismic wave velocity with spatiotemporal variations that can be detected using the CASSM method. The traveltime change is caused by CO_2 displacing brine in a fractional part of the raypath and then, as injection continues, by changing CO_2 saturation in one or more fractional parts (assuming constant raypath). The detectability of CO_2-induced traveltime change is controlled by those factors affecting the rock physics, including porosity, partial saturation, and in situ temperature and pressure.

Our initial results for five sensor locations are shown in Figure 4 in terms of crosswell delay time versus calendar time. We apply a qualitative interpretation of major features at this time. For the deepest sensor, 1680 m, the velocity change began about six hours after injection, increased for six hours, and then was stable. We interpret this to mean that after six hours a flow path reached this wave path volume (the volume of rock sampled by the first arriving wavefront). The flow path was fully developed in six hours with approximately constant spatial dimension and approximately constant CO_2 saturation (within the limits of seismic detectability). This implies that

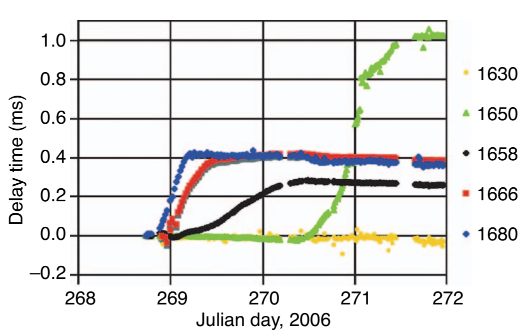

Figure 4. Delay time measurements for five sensor depths (m). Change in delay time is assumed to be caused by change in CO_2 saturation and/or plume thickness. No change is seen at the shallowest control depth (1630 m) whereas the other depths show progressively later increase in delay time with decreasing depth, thereby monitoring the upward movement of the CO_2 plume.

flow paths of CO_2 were established without further displacement of brine within this wave path volume.

Traveltime to the sensor at 1658 m shows that the initial CO_2 flow path reached the wave path volume about eight hours after injection and was fully developed after about 36 hours. The 1650-m sensor data, sampling the top of the Blue sand reservoir, show the CO_2 arrived after about 36 hours, before detection in the monitoring wellbore via fluid sampling. This result implies buoyant rise of the CO_2 to the top of the reservoir sand before reaching the monitoring well, and provides useful data for inclusion of buoyancy-driven CO_2 flow in reservoir modeling. The delay time stabilized about 60 hours after injection, implying a stable CO_2 plume/flow path between the wells. Complete processing and further quantitative analysis of this data set are planned; however, the success of the CASSM methodology, with submillisecond traveltime measurement at 15-min. intervals over multiple days of injection, is well demonstrated.

CONCLUSIONS

We have developed and deployed a novel borehole seismic source as part of a crosswell CASSM experiment to help understand CO_2 injection in saline aquifers. Having the source operate in the injection well allows crosswell monitoring without a separate seismic source borehole. Similarly, using tubing-deployed sensors allows dual use of the one monitoring well for fluid sampling and seismic monitoring during injection. Although quantitative interpretation of the Frio-II experiment is limited by sparse source-receiver coverage, future deployments can incorporate multiple sources, thus enabling acquisition of data suitable for continuous tomographic monitoring.

The relatively high level of background noise expected with injection and fluid sampling was overcome with the massive stacking available for a continuous monitoring experiment. Fluid sampling in the sensor well did increase noise levels, but not enough to compromise the traveltime measurements. Traveltime changes of 0.2 to 1.1 ms (2% to 8%) caused by a CO_2 plume were easily detected and monitored spatially and temporally with 15-minute intervals. Our field-scale application of the CASSM methodology, along with the development of a tubing-deployable source, demonstrates a novel approach for characterizing reservoir processes in situ.

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